Plans & Preliminary Results of Fundamental Studies of Ice Crystal Icing Physics in the NASA PSL

June 15, 2016

Peter Struk
NASA Glenn Research Center

Jen-Ching Tsao, Tadas Bartkus
Ohio Aerospace Institute

Outline

- Introduction & background
- NASA Fundamental Ice Crystal Icing Research Goals
  - Concepts using PSL
- Experimental Description – Preliminary 2-day test May 2015
- Results
  - Review one case in detail
  - Look at general trends from sweeping
    - Total Water Content
    - Humidity
    - Spray Bar Water Temperature
- Conclusions

Introduction

- NASA investigating the fundamental physics of ice crystal icing (ICI)
  - AEST → AATT
- Challenging to study ice-accretion physics directly inside the engine
  - Trying to simulating that environment without using engine
- Evaluating whether the NASA Propulsion Systems Lab (PSL), in addition to full-engine and motor-driven-rig tests, can be used for more fundamental ice-accretion studies
  - Paper presents concept & some preliminary experimental test results
  - Subsequent paper present complementary modelling work

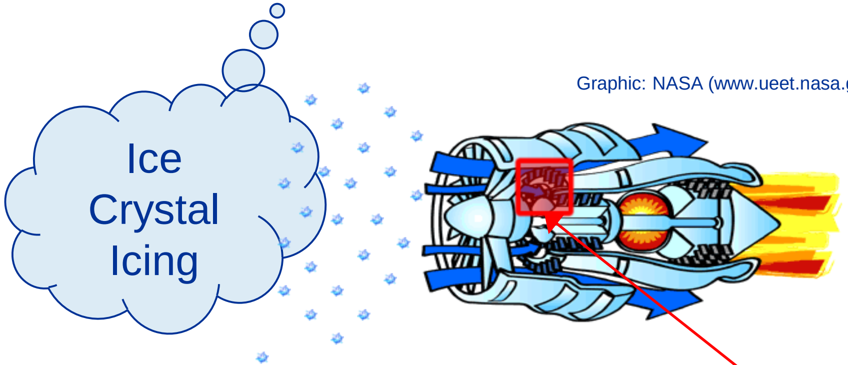
Atmospheric Environments Safety Technologies Project (AEST; 2009–2014)

Advance Air Transport Technology Project (AATT; 2015 +)
Advanced Aircraft Icing (AAI) Subproject

Technical Challenge:
Expand engine aero-thermodynamic modeling capability to predictively assess the onset of icing in current and N+2/N+3 aircraft during flight operation (FY21).

The simulation tools are well anchored in results from both fundamental physics studies and full engine tests.

NASA Fundamental ICI Goals



Graphic: NASA (www.ueet.nasa.gov)

1. Identify and bound the conditions affecting ice-crystal ice accretion at the (local) accretion site

2. Generate & characterize (i.e. measure) those conditions including uniformity

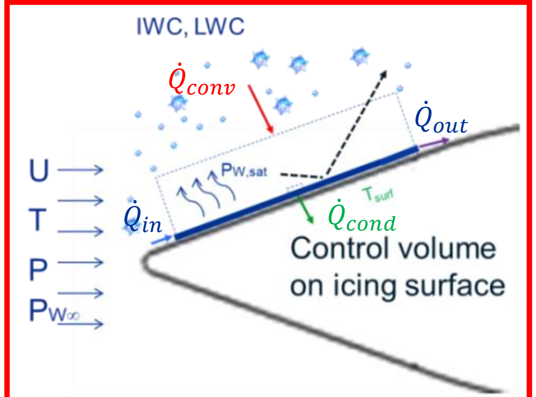
3. Gather data and develop models on ice-crystal icing factors

4. Scaling: develop & test scaling relations for ice-crystal icing

PSL Work

Key: Link actual conditions in an engine to fundamental work

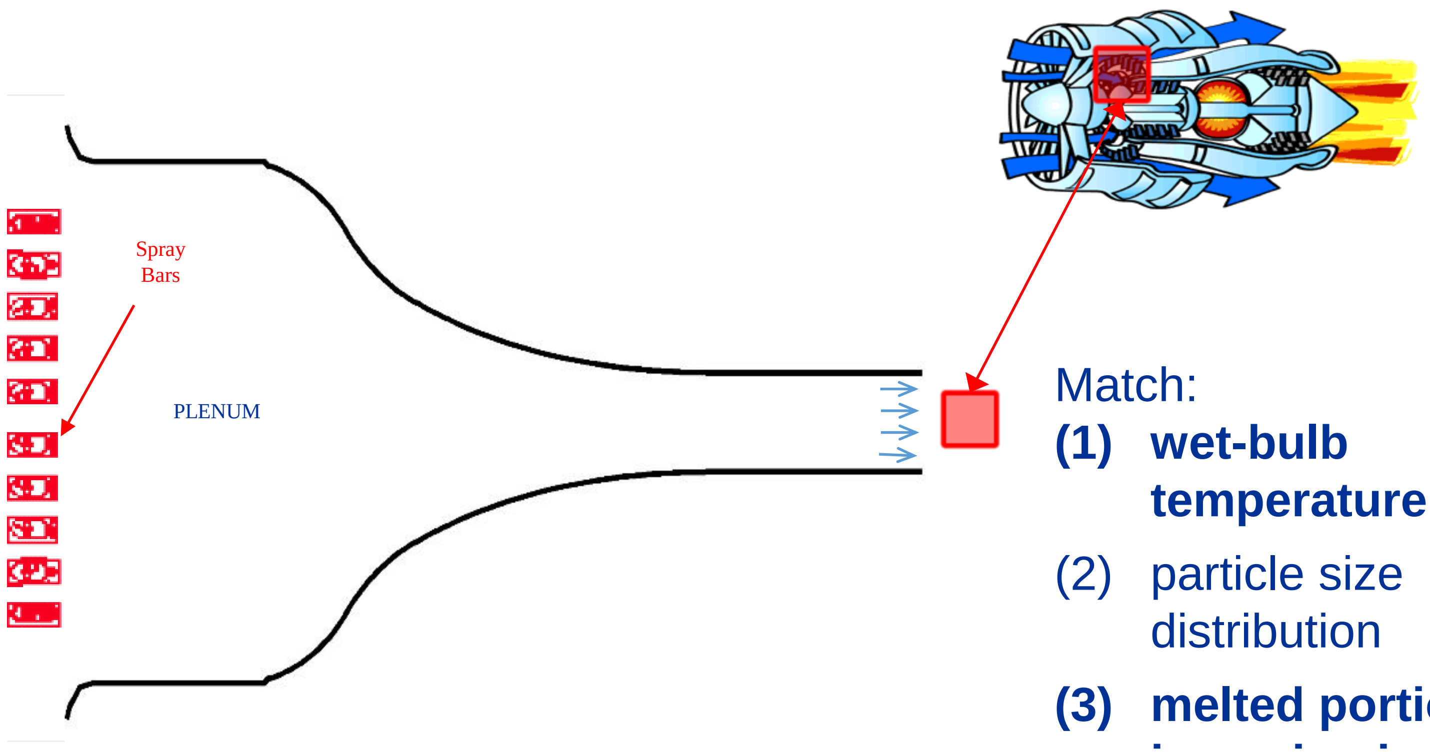
Local Region



Graphic: NASA

Local region requires more information than full-scale test (e.g. melt ratio)

Concept Using PSL



Match:

(1) wet-bulb temperature

(2) particle size distribution

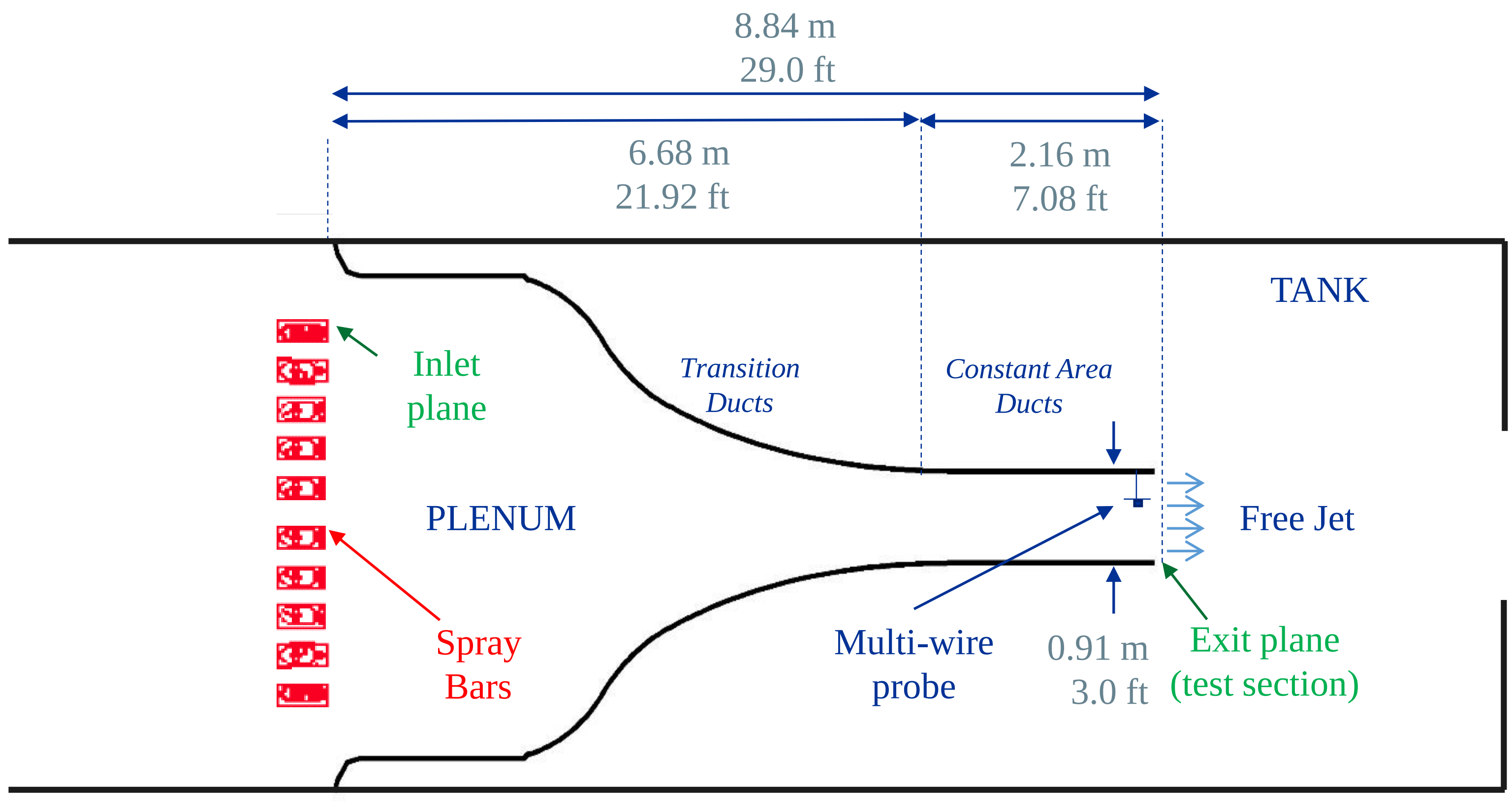
(3) melted portion of incoming ice

Goal: Ability to generate a prescribed mixed-phase condition at the test section for fundamental ice-crystal icing research

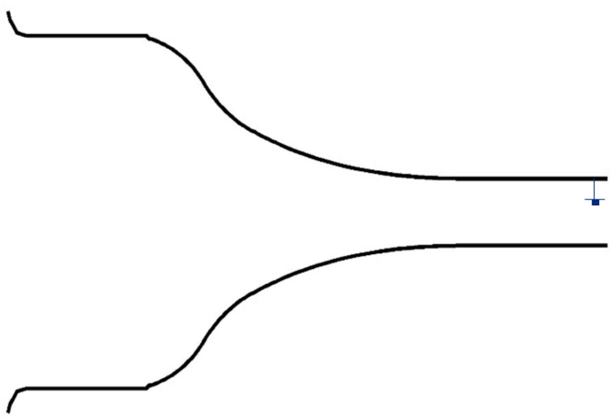
Preliminary Testing

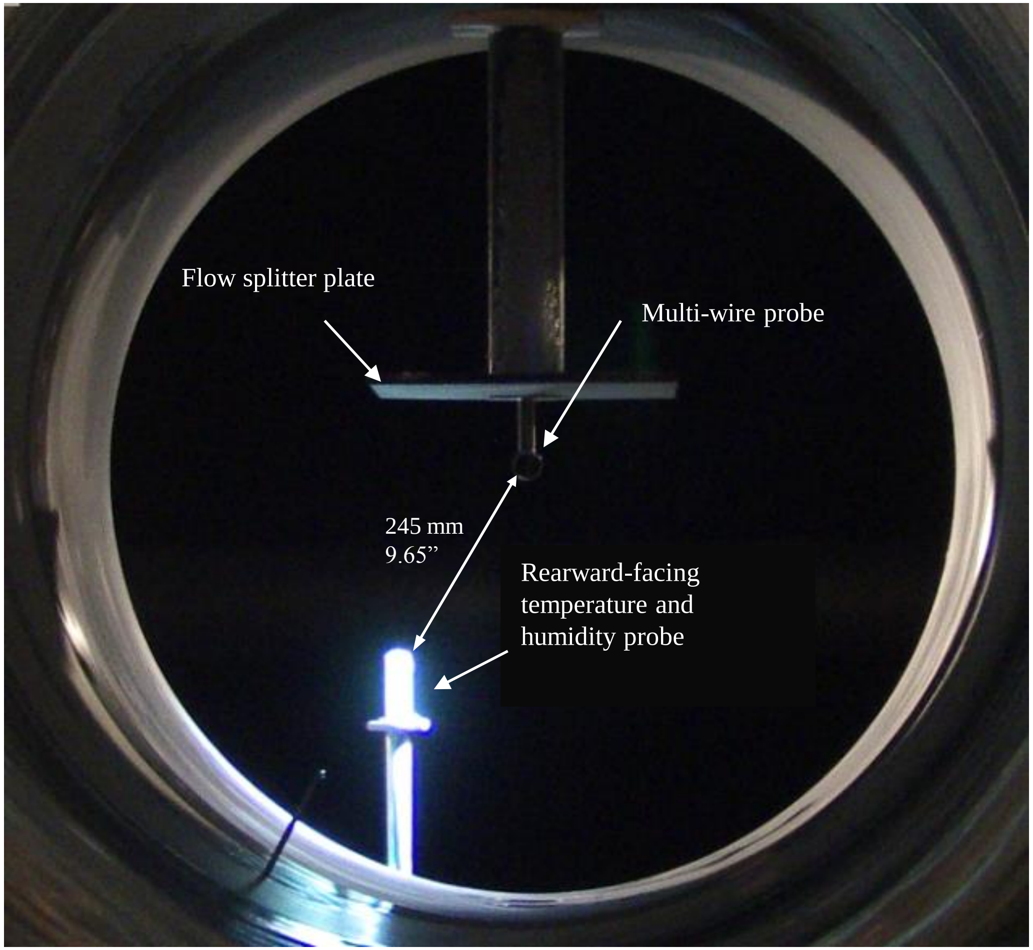
- **2 days of testing occurred in May 2015**
- **Objectives**
  - Preparation for more extensive test scheduled for 2016
  - Examine spray bar and plenum parameters and how they affect the mixed-phase at the exit of the free jet
  - Cloud characterization:
    - Melt ratio using SEA multiwire
    - Temperature & humidity measurements at test section (cloud on vs. cloud off) using custom probe
  - Observe ice accretion

PSL Configuration



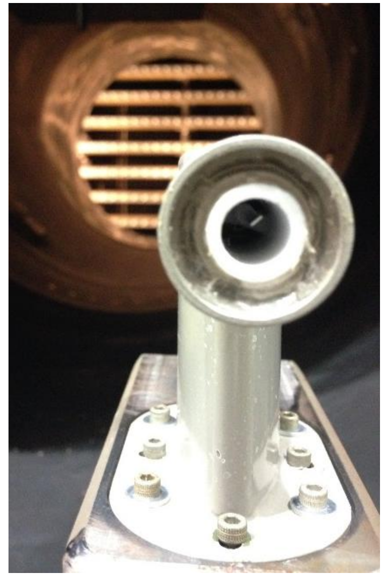
PSL Configuration (cont.)





Temperature and Humidity Measurement

Side View



Top View

Tunnel Flow

- Reward facing probe
  - Temperature
    - Resistance Temperature Device (RTD) placed inside probe inlet to prevent water / ice contamination
    - Small suction induced in probe
    - Calibrated to read total temperature given Mach
  - Humidity
    - Flow extracted via same probe inlet
    - Using Spectra Sensor Model WVSS-II
      - Tunable Diode Laser Absorption Spectroscopy (TDLAS)
  - Cameras imaged probe to observe any ice accretion

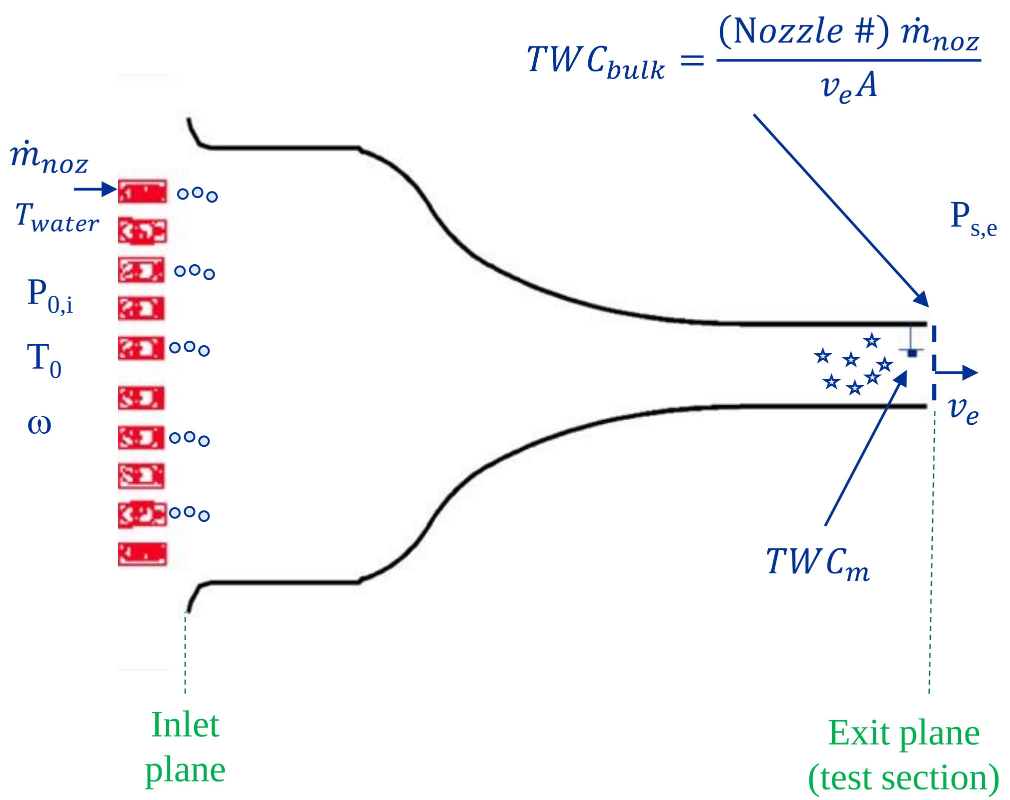
Mixed-Phase Investigation

Parameters

- Plenum / test section
  - Total pressure, $P_{0,i}$ (kPa)
  - Static pressure, $P_{s,e}$ (kPa)
    - Velocity, v_e (m/s)
  - Total temperature, $T_{0,i}$ (°C)
  - Humidity, ω_i (g / kg dry)

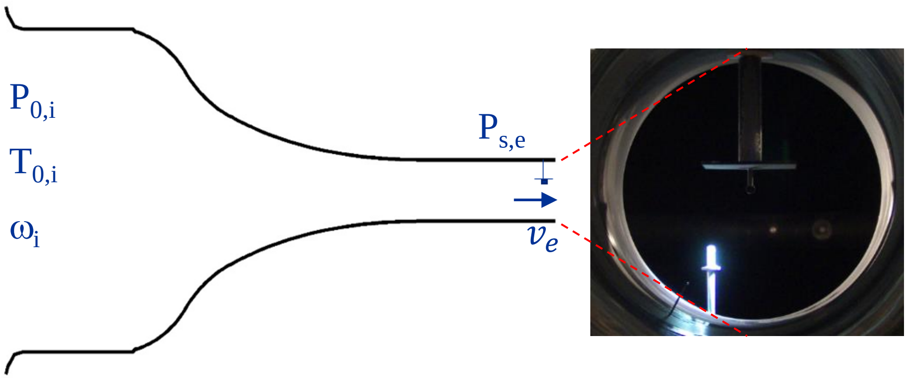
- Spray bar
  - TWC
    - P_{air} & $P_{water} \rightarrow \dot{m}_{noz}$
    - Nozzle #
  - Particle Size
    - MVDi (IRT calibrated values)
  - Water / air temperatures, T_{water}

Nomenclature



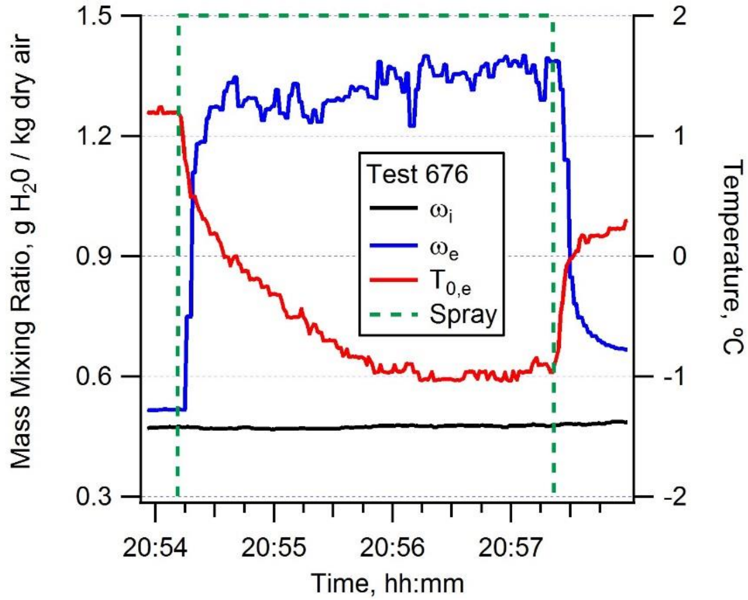
Sample Test Data

- Plenum / Test Section (targets)
  - $P_{0,i}$ = 87.3 kPa
  - $P_{s,e}$ = 83.6 kPa (1.6 km)
  - v_e = 85 m/s
  - $T_{0,i}$ = 1.8°C
  - ω_i = 0.5 g/kg dry (RH_{PL} = 10%)



- Spray bar
  - TWC_{bulk} = 1.4 g/m^3
  - MVDi = 40 µm

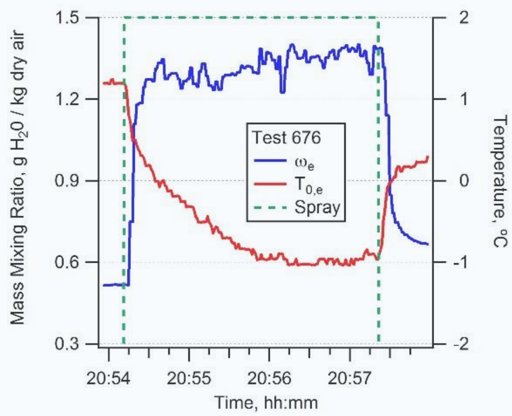
Test Section Measurements

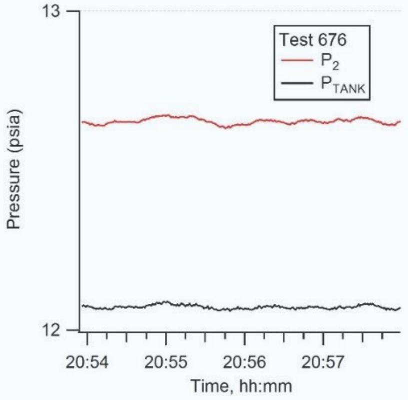


- Reported data
  - Temperature measurement lag likely due to thermal inertia of inlet
  - 30 second averages
    - Cloud off (0.52 g/kg, 1.2 °C)
    - Cloud on (1.37 g/kg, -0.9 °C)
  - $\Delta T_{0,e} = T_{0,e,on} - T_{0,e,off}$

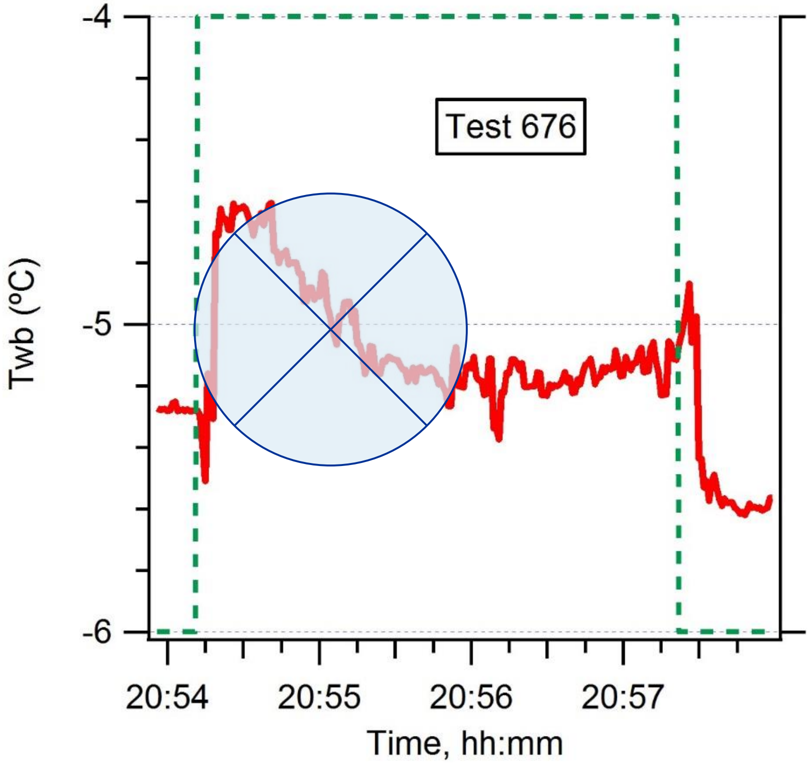
Wet-bulb temperature

INPUT



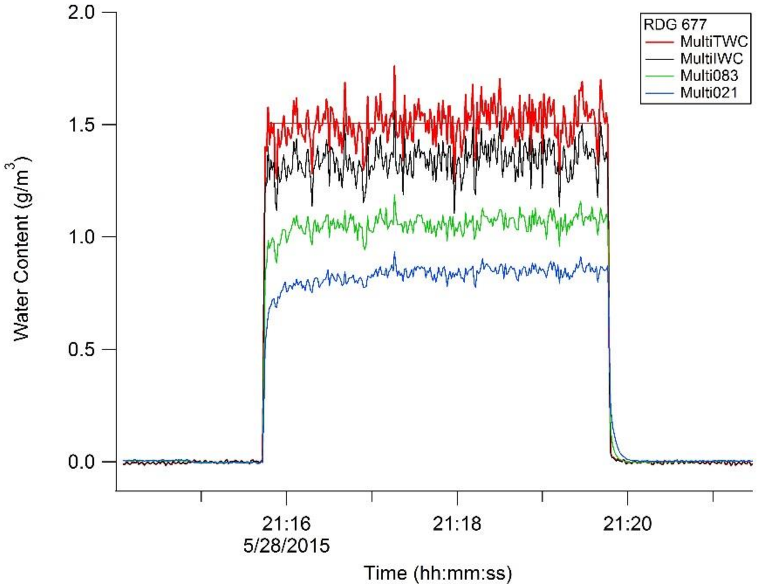


OUTPUT



Wet bulb slightly increased…typical result

Multiwire Results



- TWCbulk = 0.78 g/m^3
  - MVDi = 40 µm
- Multiwire data
  - 30 second averages
  - TWC_m = 1.50 g/m^3
  - $LWC_{m,2.1}$ = 1.06 g/m^3
  - $LWC_{m,0.5}$ = 0.83 g/m^3
  - Melt ratio, η_e

$$\eta_e = \frac{\max(LWCm)}{TWC_m} = \frac{1.06}{1.50} = 0.70*$$

* more detailed analysis anticipated to be applied later

Ice Accretion Examples

Case 677 ($\eta_e = 0.70$)

8X actual speed

Case 663 ($\eta_e = 0.20$)

Parameter Sweeps

- Paper presents parameter sweeps for the following variables:
  - TWC_{bulk} (0.5 – 5 g/m^3)
  - Plenum RH (10 – 50%)
  - Spray bar temperature (7°C, 43°C, and 82°C)

- Within each sweep, additional variations on:
  - MVDi
  - Wet-bulb temperature

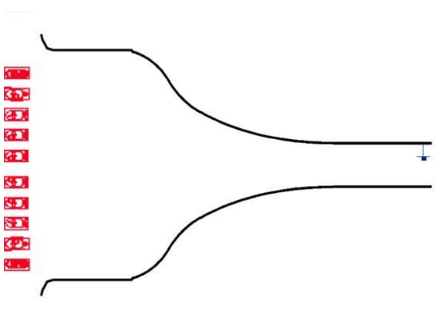


Table 2. Facility target conditions and select measurements during two TW

Test Series ->	TWC Sweep 3			
	Facility Target Condition			
$P_{0,i}$ (kPa)	87.3			
$P_{s,e}$ (kPa)	83.6			
v_e (m/s)	85			
Altitude (km)	1.6			
$T_{0,i}$ (°C)	4.2			
$T_{s,e,off}$ (°C)	0.6			
$RH_{0,i}$ (%)	10			
ω_i (g/kg)	0.6			
$Twb_{0,e,off}$ (°C)	-3			
$Twb_{s,e,off}$ (°C)	-6			
$T_{water,i}$ (°C)	7			
TWC_{bulk}(g/m^3)	0.78	1.4	2.3	5.0
MVD_i (μm)	40			
	Measurements			
Test #	670	671	672	673
TWC_m (g/m^3)	1.4	2.9	4.3	10.0
η_e (-)	0.69	0.66	0.23	0.27
$\Delta\omega_e$(g/kg)	0.55	0.87	1.3	2.3
$\Delta T_{0,e}$ (°C)	-1.7	-2.3	-2.9	-3.7
$Twb_{0,e,on}$ (°C)	-3	-4	-3	-2
$Twb_{s,e,on}$ (°C)	-6	-6	-5	-4
Ice Accr. (Y/N)	Y	Y	Y	Y

Conclusions

- NASA conducting research on fundamentals of ICI with following goals:
  - Identify and bound the conditions at the (local) accretion site
  - Generate & characterize conditions
  - Develop models & gather data on ice-crystal icing factors
  - Scaling: develop & test scaling relations for ice-crystal icing

- Generate environment outside of an engine to facilitate study
  - Evaluating PSL as potential test bed

- Presented data from an initial 2-day test effort in May 2015
  - Parameter sweeps on TWC, Plenum RH, and T_{water}
    - More limited variation on initial particle size and Twb
  - Saw both expected trends; harder-to-explain trends; new insights
    - Measurement uncertainties, cloud uniformity, and additional data required
  - Preparatory work for 2016 testing

- 2-week test campaign occurred in March 2016
  - Data analysis beginning

Acknowledgement

- Financial support:
  - NASA's, Advanced Air Vehicle’s program
    - Advance Air Transport Technology Project (AATT)
      - Advanced Aircraft Icing (AAI) – Mr. Tony Nerone, Project Manager

- Special thanks to:
  - Staff of the NASA PSL
  - Kyle Zimmerle, Michael Oliver, and Judy Van Zante who provided information presented in this paper.
  - Mr. Chris Lynch for his excellent imaging work.